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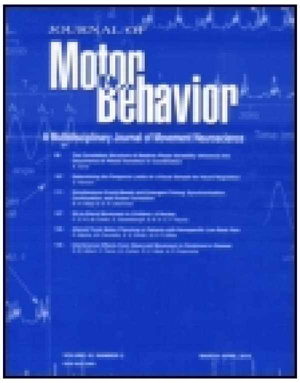
published in
Journal of Motor Behavior
2002

DOI (link to publisher)
10.1080/00222890209601955

document version
Publisher's PDF, also known as Version of record



Journal of Motor Behavior

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/vjmb20

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Version of record first published: 01 Apr 2010.

To cite this article: Matthieu Lenoir, Ellane Musch, Evert Thiery & Geert J. P. Savelsbergh (2002): Rate of Change of Angular Bearing as the Relevant Property in a Horizontal Interception Task During Locomotion, Journal of Motor Behavior, 34:4, 385-401

To link to this article: http://dx.doi.org/10.1080/00222890209601955

Journal of Motor Behavior, 2002, Vol. 34, No. 4, 385–401

Rate of Change of Angular Bearing as the Relevant Property in a Horizontal Interception Task During Locomotion

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ABSTRACT. The authors ran 3 experiments to investigate how catchers deal with the horizontal component of the ball's trajectory in an interception task during locomotion. The experiments were built upon the finding that velocity adaptations are based upon changes in the horizontal angular position or velocity of the ball with respect to the observer (M. Lenoir, M. Janssens, E. Musch, E. Thiery, & J. Uyttenhove, 1999); a potential underlying information source for that strategy is described. In Experiment 1, actor (N = 10 participants) and ball approached each other along the legs of a V-shaped track. When the velocity and the initial angular bearing of the ball were varied, the observed behavior fitted with nulling the horizontal angular velocity of the ball: A positive or negative angular velocity was compensated by a velocity change. Evidence was obtained that those adaptations are modulated by a critical change in, rather than by a critical state of, the environment–actor system. In Experiment 2, the distance between the head and an artificial end-effector was varied. Irrespective of that distance, participants (N = 7) accelerated and decelerated in order to keep the angular velocity of the ball with respect to the end-effector close to constant. The ecological relevance of that constant bearing angle strategy was confirmed in Experiment 3: Participants (N = 7) in that experiment freely ran to catch fly balls. The present results support the concept that one can explain with a limited number of control variables an actor's behavior in an interception task during self-motion.

Key words: angular constancy, interceptive timing, invariant, perception–action coupling

Catching or intercepting a ball is a crucial ability in many sports, such as basketball, soccer, tennis, baseball, or handball. That ability is reflected in the ease that an expert baseball fielder sometimes shows in successfully intercepting a seemingly impossible fly ball. Accurate pick-up of temporal and spatial information on the ball's flight is necessary for the adjustment of the hitting or grasping movement (e.g., Bootsma & Van Wieringen, 1990; Rosengren, Pick, & von Hofsten, 1988; Savelsbergh & Whiting, 1988; Savelsbergh, Whiting, & Bootsma, 1991) as well as for the control of the transport of the catcher's body toward the place where the ball will arrive (McBeath, Shaffer, & Kaiser, 1995; McLeod & Dienes, 1996; Michaels & Oudejans, 1992; Montagne, Laurent, & Durey, 1998). Apart from being able to know where to run to catch the ball, the fielder must often do so under severe temporal constraints.

Recently, the case of a baseball fielder moving to catch a ball that is hit toward him in the sagittal plane (so that no right–left movements are required) has received considerable attention. Several authors have tried to identify the strategy and the relevant property of the environment–actor system (EAS; Bootsma et al., 1997) a catcher relies on to decide, in the first place, whether to advance or retreat and, second, how fast he needs to do that in order to arrive at the landing location at the same time as the ball. The catcher seems to run forward or backward at a speed that keeps the vertical optical acceleration of the ball with respect to the launching point equal (or close) to zero (Chapman, 1968; Dienes & McLeod, 1993; Michaels & Oudejans, 1992). That strategy has been called *vertical optical acceleration cancellation* (OAC).

Many interception tasks also involve a lateral component of the trajectory of the ball. In those cases, the catcher must, in addition to a forward or a backward translation, move along the left–right axis with respect to the launching point (Chapman, 1968). It is generally agreed that zeroing out the horizontal (angular) velocity with respect to the observer is sufficient for dealing with motion in the horizontal plane (McLeod & Dienes, 1996; Michaels & Oudejans, 1992). In consequence, the combination of zeroing out the vertical

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optical acceleration and the horizontal velocity of the ball could explain interceptive behavior for all possible ball trajectories. In addition, there are plenty of situations in which movement in the horizontal plane is more important than movement in the vertical plane or is even the only movement involved. Such situations abound in sport and in traffic situations. When approaching a busy crossroad by car, a driver must accelerate or decelerate in order to avoid a collision with a vehicle approaching the same crossroad. The invariant angular position of the other car (or, equivalently, its angular velocity being equal to zero) is considered to be crucial for the modulation of that behavior (Berthelon & Mestre, 1993; Cutting, Vishton, & Braren, 1995; Janssen, 1984; Janssen & van der Horst, 1980; Warren, 1990). It is generally accepted that a player trying to intercept a moving ball is relying on the same EAS property as the driver trying to avoid a collision with another vehicle that is approaching the same crossroad (Bootsma & Oudejans, 1993; Cutting et al., 1995; Pollack, 1995). The similarity with traffic situations is very clear in sports situations such as a player running over the ground for a soccer pass or skating toward a gliding ice hockey puck.

Lenoir, Musch, Janssens, Thiery, and Uyttenhove (1999) recently obtained experimental support for a strategy relying on the use of the relative angular position or velocity of the ball. They asked participants to intercept a ball that was approaching on one leg of a V-shaped track while they moved on its other leg. Participants moved on a tricycle and tried to intercept the ball with an artificial end-effector that was attached at the handlebar of the tricycle. Lenoir and his colleagues found that observers adapted their velocity as a function of the sign and the magnitude of the angular velocity of the ball, resulting in angular velocity curves that oscillated around a zero value. More specifically, rather than using the head as the center of the angle (βh), participants kept the angular position of the ball with respect to the end-effector (βe) close to constant. That strategy has been called the *constant bearing angle* (CBA) strategy. In answer to the question of how that EAS property can be visually extracted, Lenoir, Musch, et al. (1999) suggested that βe can be optically specified as follows:

$$\beta e = \arctan[(l * \tan \beta h)/(l - d * \tan \beta h)], \tag{1}$$

where l is the distance between the ball and the end-effector and d is the distance between the eye and the end-effector. Information on βh, l, and d is potentially available through the visual channel.

Our purpose in the work reported herein was to extend the findings of Lenoir, Musch, et al. (1999) along three lines of reasoning. The central question in Experiment 1 was whether a velocity adaptation occurs as a function of a particular absolute value of βe or as a function of its first derivative. In other words, do we act upon a certain critical state in the EAS or upon a critical change in that state? Although he did not totally exclude the role of the relative angular velocity, Janssen (1984; Janssen & van der Horst, 1980) suggested that in traffic situations, the observer uses the optical position of the opponent mobile to adapt that speed. Lenoir, Musch, et al. also discussed that particular issue, but no thorough attempt has yet been made to exclude either of the two potential control variables. For that purpose, we provoked more pronounced and more distinct velocity changes in Experiment 1. If $d\beta e/dt$ is the primal control variable, a significant change in velocity should be preceded by a deviation of $d\beta e/dt$ from zero, irrespective of the absolute value of βe. Alternatively, velocity changes occurring in response to a certain value of βe, irrespective of the magnitude of its first derivative, would argue in favor of a control variable that does not involve time.

In Experiment 2, we varied the influence of the distance between the end-effector and the point of observation (distance d in Equation 1) between 0 and 120 cm to test whether the CBA strategy would hold. That is, does the strategy hold when the relation between βe and βh is changed? In previous research on the constancy of $d\beta e/dt$ and βe, the bearing angle of the ball with respect to the head (βh) was also relatively close to constant in the first half of the trajectory, leaving room for different substrategies during the task: After starting with βh close to constant in the first half, participants could switch to a homing-in strategy in which the angular constancy of the ball with respect to the end-effector might be no more than a geometrical coincidence. If participants use a head-centered strategy and switch to final adjustments near the end of the trajectory, βh should remain constant during a large part of the transport phase, irrespective of the distance between the head and the end-effector (although one might expect that the homing-in phase would occur earlier as the distance head–end-effector increases). On the other hand, if $d\beta e/dt$ is the EAS property observers use in the control of their velocity during the transport phase, a near constant angle βe would be expected over the whole trajectory.

The apparent reliance on the CBA strategy (Lenoir, Musch, et al., 1999; Lenoir, Savelsbergh, et al., 1999) might well be the result of the specific task constraints, such as the straight approaches and the constant velocity of the ball. The ecological relevance of the general CBA strategy must be tested in a real catching task (see Chapman, 1968; Montagne et al., 1998). Therefore a third experiment was conducted in which participants freely ran to catch soccer balls. Our working hypothesis in that experiment was that participants would act so as to keep $d\beta/dt$ close to zero in that more natural and less restricted task.

EXPERIMENT 1

Method

Participants

Ten students (5 men and 5 women, aged 20.2 ± 1.0 years) at the Institute for Physical Education participated in the experiment on a voluntary basis. All participants preferred their right hand in catching balls and had normal or corrected-to-normal vision. None were familiar with the hypotheses of the experiment or had previously been involved in similar experiments. As physical education students, they had experience in several ball games.

Task and Apparatus

A modified version of the apparatus designed by Lenoir, Musch, et al. (1999) was used. Basically, the participant and the ball approached each other along the two legs of a V-shaped track (Figure 1). The participants moved on a tricycle and tried to intercept the ball at the crossing of both trajectories. More specifically, the task was to obtain contact between the ball and a white plate (8 cm high and 1 cm wide) fixed to the handlebar at 60 cm from the head. The floor, walls, and ceiling of the room were covered with black plastic so that visual information from the environment was reduced. The trajectory of the ball was illuminated by a series of TL-lights.

Ball chute. The ball was attached to the bottom of a little car that was electrically driven in a chute 2.30 m above the ground. The car was propelled by a 12-V-driven pulley system, as shown in Figure 2. A nylon rope connected two pulleys, one on the motor axis and one at the other end of the chute. The rope passed through a hole in a wooden block on top of the car, except for two knots that could pull the car back and forth through the chute. The low weight of the car–ball system (less than 0.1 kg) reduced its inertia to a negligible value. The velocity of the ball was measured by means of two microswitches in the left side of the rail. The three velocities of the ball were 1.55 ± 0.03, 1.84 ± 0.04, and 2.63 ± 0.06 m/s. Those velocities remained constant throughout the trajectory.

Participants' Trajectories

A rail in which the front wheel of the tricycle was conducted prevented deviation from the straight path. A V-formed construction in front of the rail enabled the participants to steer their front wheel in the rail without paying much attention to it. Participants started in the adjoining room and attuned their velocities to a digital speedometer fixed on the handlebar: That procedure resulted in an initial velocity of 2.02 ± 0.10 m/s. At 6 m in front of the experimental room, that is, after an initial run-up of 15 m, a switch on the floor set the motor–ball system going when the front wheel pushed in the switch. When the participants entered the experimental room, the ball was at one of the three possible initial angular positions (IAPs) with respect to the end-effector: 67.5° ± 1.6° (IAP68), 85.5° ± 1.0° (IAP86), or 103.2° ± 2.0° (IAP103). We obtained those IAPs by using different starting points for the knot in the rope so that it reached the car after a longer or a shorter time interval. For example, the starting position of the knot was 2.0 m closer to the motor axis in IAP68 than in condition IAP86. In combination with the different ball speeds, the differences in starting points resulted in initial angular velocities of the ball (with respect to the end-effector) ranging from 4.2° ± 0.8°/s (combination of IAP103 and 1.55 m/s) to –6.8° ± 1.2°/s (IAP68 and 2.63 m/s). A negative sign specifies that the angle was decreasing—in other words, that the participant was lagging behind.

Procedure

Participants intercepted 10 balls in each of the nine (3 velocities × 3 initial angles) conditions in two sessions of 45 trials on 2 separate days with a 1-week interval. Conditions were presented in a random order that was the same for all participants. The same condition was never presented in more than 3 consecutive trials. On entrance into the experimental room, participants read the task instructions and practiced to match their cycling pace with a fixed velocity on the speedometer. They were instructed to enter the

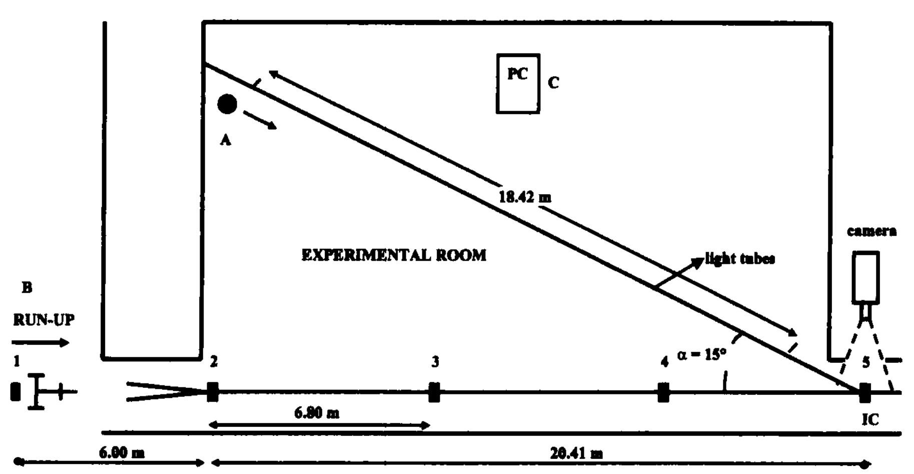

FIGURE 1. Top view of the experimental room (not drawn to scale). **A.** trajectory of the ball; **B.** participant–tricycle system; **C.** registration unit. Number 1 represents the switch that set the ball in motion; and numbers 2 to 5 represent the switches at the start, one-third, and two-thirds of the trajectory, and at the interception point (IC).

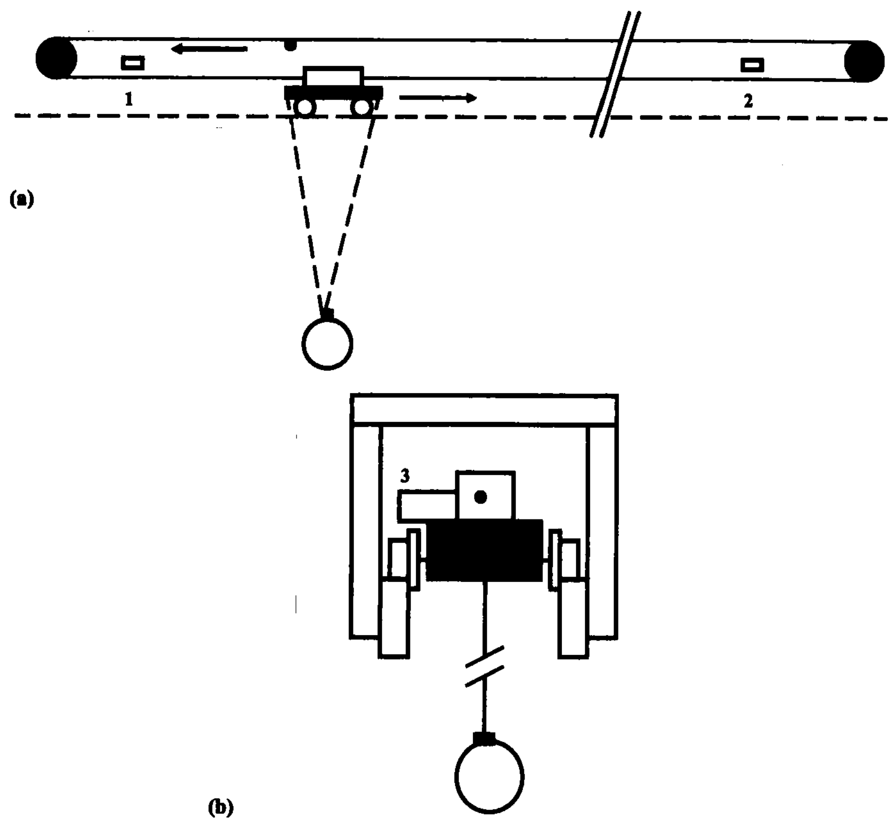

FIGURE 2. Lateral view (a) and cross-section (b) of the chute and the car–ball system. The black dots represent the knots in the rope; numbers 1 and 2 represent the microswitches that were activated by a pin on top of the car (3).

experimental room at the imposed velocity and to then try to make the front side of the white plate collide with the ball at the point where both trajectories crossed. No further information was given on how to achieve that goal. When the participants were sufficiently acquainted with the imposed initial velocity, 3 practice trials were presented in Condition IAP86 at the intermediate velocity. Participants wore headphones to reduce the information that might possibly come from the noise of the wheels of the car (Rosenblum, Carello, & Pastore, 1987).

Data Acquisition and Dependent Variables

Interception scores. The interception phase was filmed laterally with a Panasonic AG-455E camera at a frequency of 25 Hz. The temporal error (binned in intervals of 50 ms) was measured from those images at the moment the ball reached the interception point. A trial was credited with the criterion score of zero if the front of the white plate was in contact with the back of the ball when the latter was at the point of interception. That point was marked on the wall facing the camera. In case of an early arrival (i.e., when the end-effector was at the interception point before the ball), a negative score was adjudged, and vice versa for a late arrival. Temporal and spatial accuracy were measured by the constant and absolute errors (*CE* and *AE*, respectively), and variability was expressed as variable error (*VE*). See the Appendix for measurement resolution with a 25-Hz camera.

The velocity of the ball was calculated from the time interval between the activation of the microswitches in the chute. The velocity of the participants during the approach phase was registered by means of an infrared (IR) ray system on the rear axle of the tricycle. The IR ray was interrupted 180 times during each full rotation of the wheel by a metal disc with 180 indentations. The pulses were converted into a continuous current and registered at 250 Hz. We used the four switches on the floor to calibrate that current/velocity ratio and to determine the starting point for all further calculations. Combination of those three signals enabled us to calculate the following variables: instantaneous position and velocity of the participant on the trajectory and angular position (βh and βe) and angular velocity (*d*βh/*dt* and *d*βe/*dt*) of the ball with respect to the participant's head and the end-effector, respectively.

Critical Values of βe *and d*βe/*dt*

In the research literature, the resulting pattern in tasks in which observers try to regulate their behavior as a function of an invariant has been reported to be oscillatory in nature (Lenoir et al., 1999; Yilmaz & Warren, 1995). Preliminary inspection of the present curves of velocity and βe confirmed that finding (Figure 3). To obtain the critical values of βe and $d\beta e/dt$, we determined the significant changes in the velocity pattern of all trials. A significant change was defined as an acceleration or deceleration of at least +0.10 m/s² or −0.10 m/s², respectively, during at least 700 ms. A plateau was defined as the absence of any acceleration during at least 700 ms. Similarly, an increase, decrease, or plateau in βe was determined when βe rose or fell at least 1°/s during at least 700 ms. For each critical value in the velocity patterns, the preceding critical value in βe was considered as the corresponding value. That procedure resulted in the critical values of βe and $d\beta e/dt$ (for a more detailed description of that procedure, see Lenoir, Musch, et al., 1999). We performed a regression analysis of $d\beta e/dt$ on velocity changes, using data points of all nine experimental conditions. A total of 3,256 points were identified, of which 799 (24.6%) were plateaus, 1,333 (40.9%) were decelerations, and 1,124 (34.5%) were accelerations.

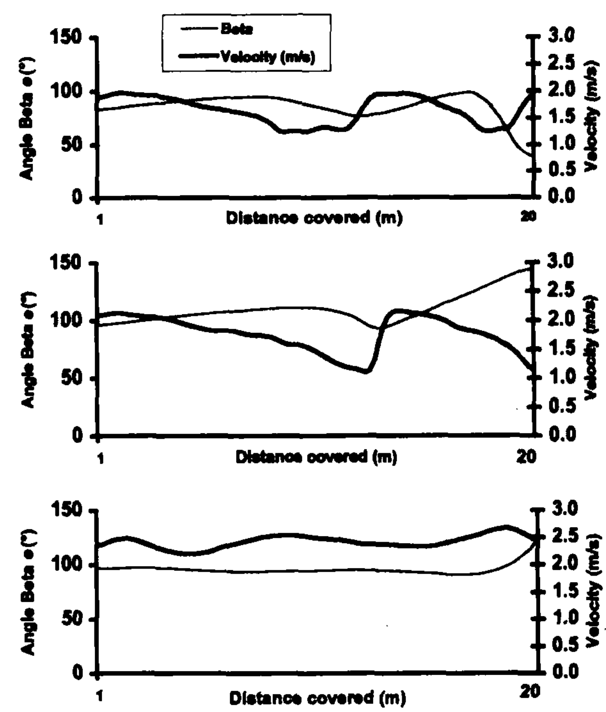

FIGURE 3. Typical plots of Beta e (thin lines) and the participant's velocity (thick line) for the three ball velocities in Condition IAP86. **Top.** 1.55 m/s; **middle**, 1.83 m/s (an early arrival); **bottom**, 2.63 m/s. Beta e is the angle between the ball–end-effector line and the participant's direction of motion. IAP86 = initial angular position 86°.

Results

Initial Conditions

We used a 3 (IAP) × 3 (ball velocity) repeated measures analysis of variance (ANOVA) to check if the participants' initial velocity and acceleration in the nine conditions were comparable with each other (Table 1). Initial velocity, $F(2, 18) = 4.902$, $p < .05$, and acceleration, $F(2, 18) = 48.903$, $p < .001$, increased with decreasing IAP. Post hoc Newman–Keuls showed that participants initially drove faster in the IAP68 condition than in both other conditions, whereas acceleration was different in all three conditions. An effect of velocity of the ball was also found:

TABLE 1
Initial Velocity (m/s) and Acceleration (m/s²) of the Participants for Different Ball Velocities and Different Initial Angular Positions (IAPs) in Experiment 1

Measure	IAP68 *M*	IAP68 *SD*	IAP86 *M*	IAP86 *SD*	IAP103 *M*	IAP103 *SD*
1.55-m/s ball velocity						
Velocity	1.98	0.06	1.89	0.08	1.88	0.08
Acceleration	0.21	0.06	0.13	0.02	0.10	0.03
1.86-m/s ball velocity						
Velocity	2.07	0.09	2.02	0.13	2.00	0.06
Acceleration	0.28	0.09	0.12	0.08	0.07	0.05
2.63-m/s ball velocity						
Velocity	2.13	0.12	2.13	0.13	2.12	0.09
Acceleration	0.36	0.14	0.12	0.05	0.09	0.05

Note. IAP68, -86, and -103 = the initial angular positions of the ball with respect to the end-effector, that is, 67.5 ± 1.6°, 85.5 ± 1.0°, and 103.2 ± 2.0°, respectively.

Higher velocities and accelerations occurred with increasing ball velocity, $F(2, 18) = 42.233$, $p < .001$, and $F(2, 18) = 3.671$, $p < .05$, respectively. Post hoc Newman–Keuls revealed that all conditions differed from each other. Those effects were caused by the particular setup: When the ball is moving faster or at a smaller angle with respect to the observer, it becomes visible sooner, which might stimulate the observer to accelerate earlier in the trajectory. Although those differences were not deliberately provoked, they did not interfere with the hypotheses tested in this experiment.

Interception Scores

A 3 (velocity) × 3 (IAP) repeated measures ANOVA was performed on *CE*, *AE*, and *VE*. A significant effect of velocity was found on all three error scores, meaning that the faster trials were characterized by higher accuracy and consistency: For *CE*, *AE*, and *VE*, *F*s ((2, 18) = 10.261, 32.135, and 22.373, all *p*s < .001 (Figure 4). A Newman–Keuls post hoc test revealed that *CE* was closer to zero in the fastest trials than in the other velocities ($p < .05$). The negative *CE* values reflected the fact that participants arrived too early in most of the trials. *AE* in all three velocities significantly differed from each other; the higher velocities led to a smaller *AE*, and the same pattern was found for *VE*. No main effects of IAP were found, $F(2, 18)$ values for *CE*, *AE*, and *VE* scores were 2.441, 0.733, and 2.088, respectively (all *p* values were greater than .05, *ns*), and no interactions occurred.

Average Angular Positions

The average βe values over the trajectory are given in Figure 5. A 3 (velocity) × 3 (IAP) ANOVA revealed that the average angular position decreased with increasing velocity of the ball, $F(2, 18) = 20.889$, $p < .001$. Post hoc tests indicated that all three angular positions differed from each other. A significant IAP effect, $F(2, 18) = 1570.566$, $p < .001$, showed that all average βe values significantly differed from each other. No significant difference between the mean βe values and the IAP was found, $F(1, 18) = .764$, *ns*. The IAP × Velocity interaction, $F(4, 36) = 10.416$, $p < .001$, revealed that the velocity effect was much more pronounced in the IAP68 and IAP86 conditions than in IAP103.

Critical βe and *d*βe/*dt* values were analyzed by means of a 2 (time of calculation: acceleration, deceleration) × 3 (IAP) × 3 (velocity) repeated measures ANOVA. Accelera-

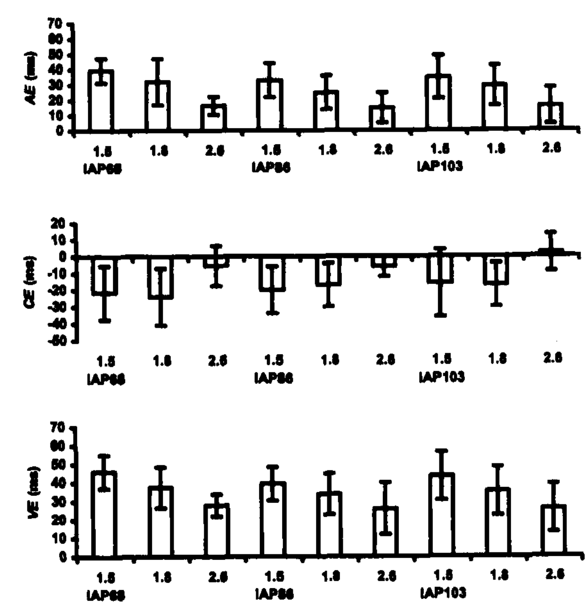

FIGURE 4. Absolute, constant, and variable error (*AE*, *CE*, and *VE*) scores for the three velocities (1.5, 1.8, and 2.6 m/s) and the three initial angular positions (IAPs 68°, 86°, and 103°) in Experiment 1.

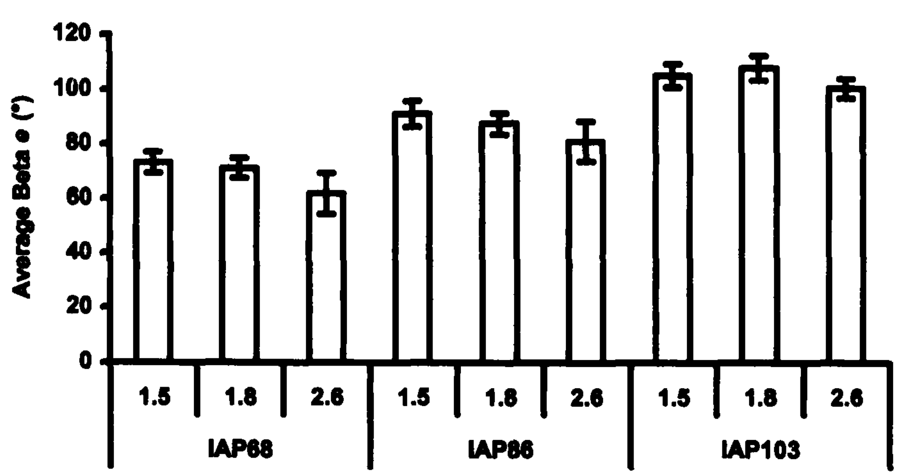

FIGURE 5. Average Beta e values in the nine experimental conditions in Experiment 1. Beta e is defined in Figure 3. IAP = initial angular position.

tions and decelerations occurred at a slightly but significantly different absolute value of βe, $F(1, 9) = 10.021$, $p < .05$: Angular position of the ball was on average 2.3° larger at acceleration (Figure 6). Critical values of βe increased with increasing IAP values, $F(2, 18) = 2161.739$, $p < .001$; all three IAP conditions were significantly different from each other. Increased βe values were also associated with lower velocities of the ball, $F(2, 18) = 18.059$, $p < .001$. Significant differences between the highest and the two lower velocity conditions were found. The velocity effect was more pronounced in the IAP68 and IAP86 conditions, as was expressed by a significant Velocity × IAP interaction, $F(4, 36) = 9.784$, $p < .001$.

Critical *d*β*e*/*dt* values were significantly smaller at acceleration than at deceleration, $F(1, 9) = 187.466$, $p < .001$, a finding that is illustrated in Figure 7. Overall, the critical values increased with increasing IAP; the values were significantly larger in the IAP103 condition than in both other conditions (1.02°/s vs. –0.08 and –0.20°/s, respectively). No main velocity effect occurred, $F(2, 18) = 1.486$, *ns*. Finally, the IAP × Velocity interaction was significant, $F(4, 36) = 5.902$, $p < .01$.

Regressions

Individual regression equations for each participant are given in Table 2, and a typical plot is shown in Figure 8. Data were grouped over all nine experimental conditions. The $|r|$ values of each participant in each experimental condition ranged from .809 to .993, with a mean value of .950 ± .02. The mean slope of the regression, that is, the value of *d*β*e*/*dt* corresponding to the participant's acceleration of 1 m/s², was –9.871 ± 0.540, ranging between –6.601 and –11.892. The

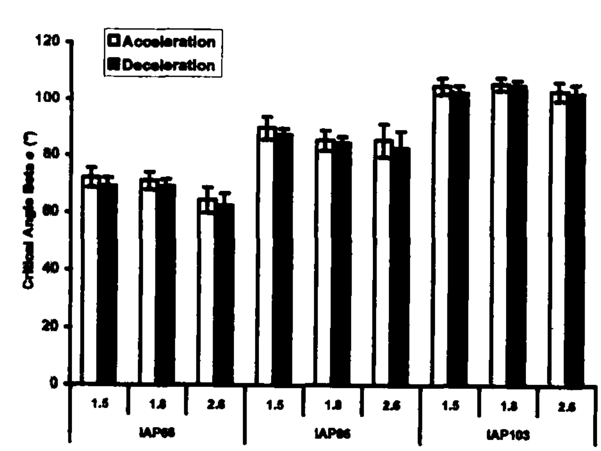

FIGURE 6. Critical values of Beta e for acceleration (white blocks) and deceleration (black blocks) in the nine experimental conditions. Means and standard deviations over participants are shown. Beta e is defined in Figure 3.

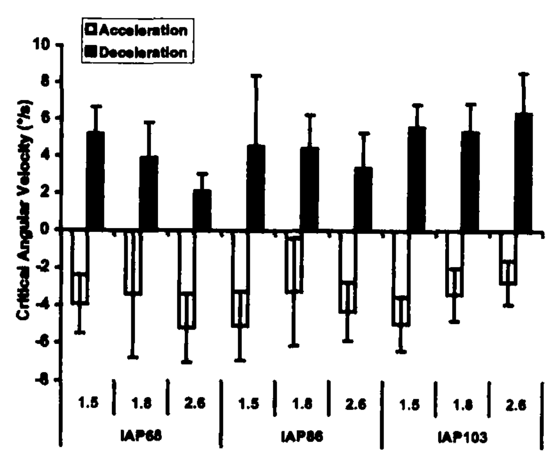

FIGURE 7. Critical values of *d*β*e*/*dt* for acceleration (white blocks) and deceleration (black blocks) in the nine experimental conditions. Means and standard deviations over participants are shown. See Figure 3 for definition of βe.

TABLE 2
Regression Equations for All Participants in Experiment 1

Participant	Regression equation	$\|r\|$	*n*
1	$Y = -8.6970x + 0.3064$	.949	332
2	$Y = -9.9588x + 0.9939$	.945	348
3	$Y = -9.4184x + 0.5507$	.939	347
4	$Y = -10.346x + 0.8186$	.960	343
5	$Y = -9.5338x + 0.4593$	.941	325
6	$Y = -10.163x + 0.9447$	.956	296
7	$Y = -10.190x + 0.5378$	.964	266
8	$Y = -10.243x + 0.5513$	.968	344
9	$Y = -9.4701x + 0.5286$	.967	351
10	$Y = -9.8948x + 0.6713$	.948	304
Total			3,256

Note. Y = angular velocity of the ball (*d*β*e*/*dt* in deg/s), x = acceleration of the participant (in m/s²), and n = number of data points.

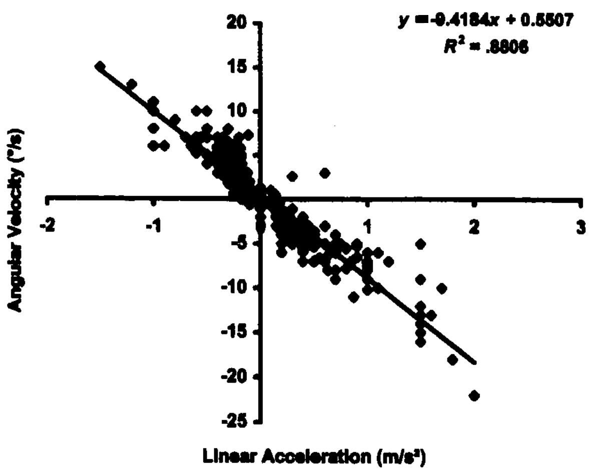

FIGURE 8. Typical regression plot of $d\beta e/dt$ over acceleration. See Figure 3 for definition of Beta e.

values of $|r|$ were independent of IAP and velocity condition, $Fs(2, 18) = .774$ and 3.806, respectively, *ns*. The slope of the regression was larger as velocity increased, $F(2, 18) = 6.953$, $p < .01$; the fastest conditions were significantly different from the lower speed conditions.

Discussion

The analysis of average βe values and regressions indicated that participants adapted their velocity pattern so that the initial angular position of the ball remained close to invariant, no matter how large or how small that angle was. Apparently, there is no such thing as an optimal βe in this particular task. At least within the range of angles provided in this experiment, participants acted so as to compensate for changes in angular velocity of the ball, irrespective of the magnitude of that angle. More solid evidence for reliance on a critical change in, rather than a critical state of, the EAS was provided by the comparison of the critical βe and $d\beta e/dt$ values. One might suppose that when the difference in magnitude of an actual and a previous βe becomes larger than the just noticeable difference (JND), participants will slow down, whereas a negative difference will cause participants to accelerate. Such a difference in behavior should have enabled us to discriminate an upper and a lower threshold of βe, with the critical values being smaller at acceleration than at deceleration: A value smaller than the optimal βe means that the observer is lagging behind and thus needs to accelerate, whereas a value larger than the optimal would result in a deceleration. However, no such phenomenon occurred in our experiment: Critical angles were even slightly larger at acceleration than at deceleration. Consequently, reliance on that positional property would not have been of great help in arriving at the right place at the right time here. The CBA strategy instead seemed to be based upon a change in the EAS: Critical values of $d\beta e/dt$ when decelerating were clearly different from critical values when accelerating ($p < .001$). Acceleration is the logical answer to a positive $d\beta e/dt$, whereas deceleration is expected when $d\beta e/dt$ becomes negative.

The IAP effects on average βe and critical βe are a logical effect of keeping $d\beta e/dt$ close to zero in the given IAP conditions: Participants did not strive for a certain optimal βe but for an invariant $d\beta e/dt$. The lower average and critical βe values for the faster condition also stemmed from design characteristics. Analysis of the initial conditions has already revealed that velocity affected the IAPs, leading to lower βe values for higher velocities. The IAP × Velocity interaction for critical $d\beta e/dt$ values is hard to interpret in a meaningful way, especially because no interaction with the moment of calculation of $d\beta e/dt$ (acceleration or deceleration) occurred.

In sum, the results reported here supported the view that the control of velocity during the transport phase could be modulated by a change in sign and in the magnitude of that change in $d\beta e/dt$ rather than by the absolute value of βe.

EXPERIMENT 2

Method

Participants

Eight students (7 men and 1 woman, 20.5 years old [range = 19–22 years]) at the Institute for Physical Education volunteered for the experiment. All claimed to be right-handed catchers and had normal or corrected-to-normal vision. None were familiar with the hypotheses in the experiment or had been involved in similar experiments. As physical education students, they had experience in several ball games.

Apparatus and Procedure

The apparatus and procedure were basically identical to those used in Experiment 1, except for the following adaptations. Participants intercepted the ball in four different ways: by touching the ball with the forehead (Condition Head) or by touching the ball with a small plate (8 cm high and 1 cm wide) that was attached to the handlebar of the tricycle and at eye height, which was equal to ball height, at a distance of 30 cm (Condition 30), 60 cm (Condition 60), or 120 cm (Condition 120) from the eyes (Figure 9). The velocity of the ball was always 2.07 ± 0.05 m/s.

To obtain uniformity in the initial velocity conditions, we instructed participants to attune their velocity to the pace of a metronome: That procedure guaranteed that they entered the experimental room at a velocity of 1.98 ± 0.06 m/s (corresponding to a cycling pace of 33 pedal rotations per minute). That rate was about 7% lower than the velocity needed to obtain a successful interception, a difference that we intentionally introduced to avoid the possibility that once the participants were inside the experimental room they would continue cycling at the same pace. After reading the task instructions, participants practiced to match their cycling pace with the metronome. The metronome was positioned so that participants could not hear its pace once they had entered the experimental room. After each trial, an experimenter controlled whether participants really followed the imposed rhythm. If they did not, the trial was repeated (0.6% of the trials required a repetition). When they were able to follow the rhythm successfully, the experiment was started. Participants wore headphones in order to reduce the information that might possibly come from the noise of the car wheels in the rail. The metronome pace still could be heard during the run-up. On entrance in the experimental room, the angular position of the ball with respect to the point of contact (or the end-effector) was 76.7° ± 3.5° for all four end-effector conditions. We achieved that uniformity by using different starting points of the knot in the rope so that the knot reached the car after a longer or shorter time interval. For example, the starting position of the knot was approximately 60 cm closer to the motor axis in the 120 condition than in the 60 condition.

Participants intercepted 120 balls in each condition on 2 separate days, with a 1-week interval. On each day, two conditions (two blocks of 30 trials) were presented. We randomized the order of conditions over participants to avoid systematic order effects. Between the sessions, a 10-min rest was provided; during that time, the experimenters prepared the tricycle for the subsequent condition. When the last session was completed, participants were asked to rank the four conditions from *easiest* to *most difficult*. The easiest condition was given a score of 4 points, the most difficult condition a score of 1. Scores were added up for each condition. They were also asked to indicate whether they were aware of any strategy they had used during the task: They had to describe what they paid attention to in order to be successful in this task.

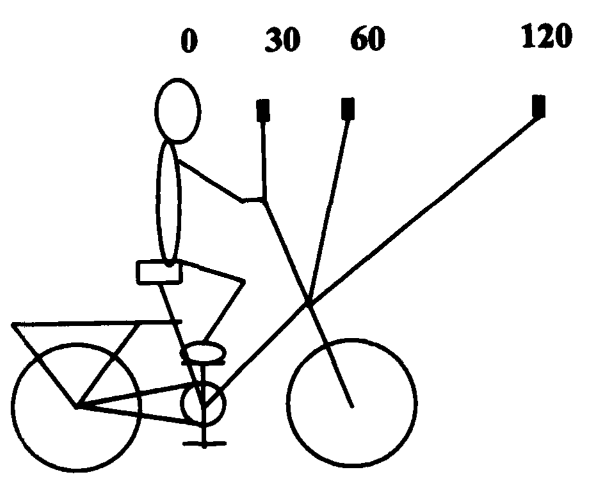

FIGURE 9. The four experimental conditions for intercepting the ball in Experiment 2: at distances of 0, 30, 60, or 120 cm in front of the head.

Data Acquisition

Velocity patterns and angular position–velocity of the ball with respect to the participant's head and the end-effector were analyzed in the same manner as in Experiment 1. The same accuracy and consistency scores were obtained from the video frames of the interception phase at a 50-ms accuracy.

Results

To ensure that the initial conditions in the four interception modes were comparable with each other, the initial velocity, acceleration, and end-effector-centered angle βe were compared with each other. A repeated measures ANOVA revealed no differences for any of those variables between the four conditions (see Table 3).

Subjective Strategies

Participants ranked the experimental conditions according to the perceived degree of difficulty. A chi-square test revealed that the experimental conditions were not of equal difficulty, $\chi^2(3, N = 8) = 9.53, p > .05$. Touching the ball with the forehead was considered the easiest condition, whereas participants claimed that they had the most problems in Condition 120. When asked what they paid attention to during the transport phase, 7 of the 8 participants claimed that they tried to keep the ball at some constant position relative to the end-effector, irrespective of its dis-

TABLE 3
Initial Velocity (m/s), Acceleration (m/s²), and Angle βe (deg) for Different Eye–End-Effector Distances in Experiment 2

	Head		30		60		120		
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*(3, 15) value
Velocity	1.98	0.07	1.98	0.06	1.97	0.06	1.98	0.04	0.270, *ns*
Acceleration	0.30	0.06	0.30	0.05	0.29	0.04	0.31	0.03	0.863, *ns*
βe	76.1	3.7	76.3	2.5	76.0	3.1	78.4	4.8	0.501, *ns*

Note. In Conditions Head, 30, 60, and 120, participants touched the ball with the forehead or with a small plate placed at eye level, 30, 60, or 120 cm from the eyes, on the handlebar of the tricycle.

tance from their head. One participant also reckoned with the angular position of the ball but could not distinguish whether it was the position relative to the end-effector or to his head.

Interception Scores

Figure 10 shows the error scores measured from the video recordings of the interception phase. Except for *VE*, scores generally tended to improve with decreasing distance between head and end-effector. A repeated measures ANOVA revealed a significant effect of distance between the head and end-effector for all three error scores, $Fs(3, 21) = 12.222$, 9.030, and 10.615, all $ps < .001$, respectively, for *CE*, *AE*, and *VE*. A post hoc Newman–Keuls test revealed that *AE* and *VE* scores were significantly better in Condition Head than in the three other conditions ($p < .05$). *CE* scores were significantly smaller in Conditions Head and 30 than in Conditions 60 and 120.

Transport Phase

In Figure 11, average curves of a representative participant in the four conditions are shown. In all four conditions, the angular velocity of the ball with respect to the end-effector remained close to constant until shortly before the interception (less than 2 m, or 1 s before contact), whereas the angular velocity with respect to the head was clearly negative very early in the trajectory (except, of course, in Condition Head). As noted earlier, the sudden increase or decrease at the end of the βe and *d*βe/*dt* curves was caused by the final scores on the interception phase: A too early or too late arrival caused the βe curve to deviate from a straight line.

Mean *d*βe/*dt* Values

The mean values of *d*βe/*dt* over the trajectory were –0.54°, 0.054°, 0.135°, and 0.161°/s, respectively, for Conditions Head, 30, 60, and 120—very close to the predicted value of zero. Separate one-sample *t* tests confirmed that the mean values did not significantly differ from zero in any of the four conditions (*t* values = –1.981, –0.387, 0.763, and 0.385, respectively, for the four conditions, *ns*). A repeated

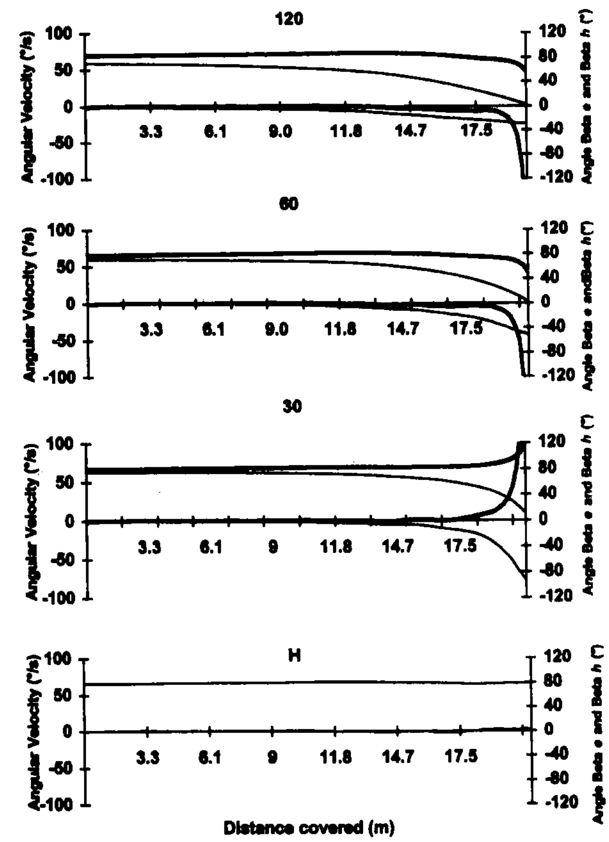

FIGURE 11. Evolution of the angular position of the ball with respect to the head (Beta h; thin upper lines) and with respect to the end-effector (Beta e; thick upper lines), and their first derivatives (thin and thick lower lines, respectively). Average curves of a representative participant are presented.

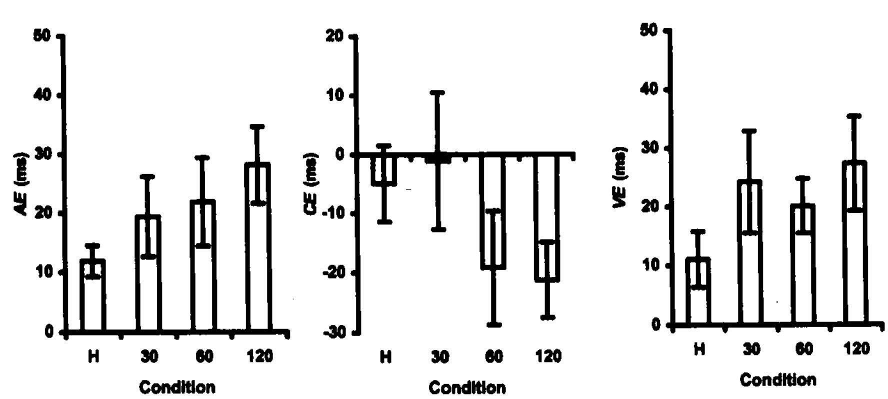

FIGURE 10. Absolute, constant, and variable error (*AE*, *CE*, and *VE*) in the four interception modes in Experiment 2.

TABLE 4
Regression Equations for All Participants in Experiment 2

Participant	Regression equation	$\lvert r \rvert$	n
1	$Y = -4.843x - 0.0855$	.754	494
2	$Y = -5.8596x - 0.3120$	.821	649
3	$Y = -5.3225x - 0.0725$	.856	650
4	$Y = -3.8740x - 0.1560$	.800	768
5	$Y = -3.4379x - 0.0322$	.864	620
6	$Y = -6.8584x - 0.1720$	.746	709
7	$Y = -4.096x - 0.0190$	.801	652
8	$Y = -5.7292x - 0.3050$	.905	618
Total			5,160

Note. Y = angular velocity of the ball, $d\beta e/dt$ (deg/s), x = acceleration of the participant (m/s^2), and n = number of data points.

measures ANOVA showed that the average $d\beta e/dt$ was equal in the four conditions, $F(3, 21) = 1.453$, *ns*.

Regressions

A total of 5,160 plateaus (1,290 or 25.0%), decreases (1,681 or 32.6%), and increases (2,189 or 42.4%) were identified. Regressions of $d\beta e/dt$ over accelerations were performed (Table 4). Repeated measures ANOVAs revealed that the $\lvert r \rvert$ values of the regression plots were the same for the four experimental conditions (.87, .89, .85, and .88 for Conditions Head, 30, 60, and 120, respectively), $F(3, 21) = 0.194$, *ns*, as were the slopes of the regressions (respectively, −4.32, −5.06, −5.25, and −5.21), $F(3, 21) = 0.374$, *ns*. The latter result means that the observer's acceleration in response to a change in $d\beta e/dt$ was of equal magnitude in all four conditions.

Discussion

The scores of the interception phase compared favorably with the participants' subjective estimations of the task difficulty: Interceptions were more accurate and more consistent when the end-effector was closer to the eyes. The significant differences between intercepting the ball with the head and the other experimental conditions might have been partially caused by unequal task constraints, however. Analysis of the videotapes of Condition Head revealed that participants sometimes made small movements of the head to compensate for arriving too early or too late. Participants apparently used the available degrees of freedom given in the task.

The decrease in interception errors (Figure 10) for shorter head–end-effector distances indicated that the necessary information became more readily available as βe approached βh. That finding might mean that βh is used instead of βe, but that suggestion was not corroborated by the results of the approach phase: βh started to decrease long before the interception point was reached. For example, the angular position of the ball with respect to the head in Condition 120 continuously decreased, supporting the notion that an end-effector-centered strategy was used from the very beginning of the task (Figure 11). The angular velocity of the ball with respect to the end-effector remained close to zero until a short time before contact in the four experimental conditions. The $\lvert r \rvert$ values of the regressions of $d\beta e/dt$ over acceleration were high and were independent of the distance between the point of observation and the end-effector. That finding provides support for the concept of an end-effector-centered CBA strategy in this particular task. If participants take into account the angular velocity of the ball, then it is more likely the velocity with respect to the end-effector than with respect to the head. The quasi-constant βh curves in Conditions 30 and 60 during the first part of the trajectory can then be considered as a geometrical consequence of using $d\beta e/dt$ rather than an argument for a head-centered strategy. Nevertheless, βh might play a part in the control of the final adjustments for the interception, causing the earlier mentioned decrease in error as βe approached βh.

EXPERIMENT 3

Method

Participants

Seven physical education students (aged 21.1 ± 1.1 years) with experience in competition basketball, handball, or soccer volunteered in the experiment. All were unaware of our purpose in the experiment.

Apparatus and Procedure

Soccer balls were launched with a soccer machine (Jugs, Inc., Tualatin, OR) at an initial velocity of 16.2 m/s and a launching angle of 26°, resulting in landing locations approximately 21 m from the machine. The time of the launch was registered by means of an IR transmitter–receiver located on the front of the machine. We laterally videotaped the middle part of the trajectory of the ball at

200 frames/s in order to obtain the highest point of the trajectory and the time the ball arrived at that point. A light-emitting diode connected to the IR system on the launching machine was located in the field of view so that those video frames could be synchronized with the time of the launch. We used MATLAB software to reconstruct the ball trajectory of each trial, reckoning with effects of air resistance.

Participants ran to catch the ball from a distance of 18 m from the landing point, at initial horizontal angles of 60°, 90°, or 120° relative to the trajectory of the ball (Figure 12). Their approach toward the landing spot was registered by a series of 11 IR transmitter–receiver gates set 1.5 m apart along a 4-m-wide runway. We collected the 11 pulses on a personal computer, together with the pulse from the IR on the launching machine, in order to synchronize the translation of the participants with the path of the ball. Three starting conditions were imposed: Participants were asked to start either walking (W), running (I), or sprinting (S) until the ball was projected by the experimenter, a paradigm that resulted in substantial variation in the initial angular position and velocity of the ball relative to the actor. Each participant performed five consecutive trials in each of the nine conditions, the order of which was randomized over participants. Because of incomplete data acquisition, 41 trials could not be used for further analysis.

Dependent Variables

On the participant's passage at each IR gate, the horizontal angle between the direction of motion of the participant and the line head–ball (β) as well as the velocity of the participant were calculated, together with their first derivatives.

In a first analysis, we examined the predicted linearity of the β curves during the approach and compared the nine conditions by means of a 3 (approach angle: 60°, 90°, and 120°) × 3 (initial velocity: walking, running, and sprinting) repeated measures ANOVA.

Whether β is the relevant EAS property for achieving contact with the ball was tested in two ways. First, the curves of β were simulated as if the participant was not moving at all (see Michaels & Oudejans, 1992, for a similar procedure). The sooner that curve diverges from the real β curve, the more sensitive is the strategy of keeping β constant. Second, the 274 trials were divided into correct catches, early arrivals, and late arrivals. A total of 209 correct catches, 32 early arrivals (i.e., instances in which the ball was at a height greater than 4 m when the participant arrived at the interception point), and 33 late arrivals (which resulted in missing the ball) were registered. A repeated measures ANOVA on slopes and $|r|$ values (averaged within each participant) of the β curves for the three categories was performed.

Finally, regressions of $d\beta/dt$ on participants' acceleration at each IR gate were performed both for each separate condition and grouped over conditions. Data from all trials were used in that analysis. We conducted that analysis to test whether the participants adapted their behavior as a function of $d\beta/dt$ (as was found in Experiments 1 and 2).

It was notable that in this experiment, we no longer distinguished between the angular position of the ball with the end-effector (as in Experiments 1 and 2) and the angle with respect to the head, because the registration method did not allow us to do so. Our aim in this experiment was limited to testing the use of β in an unconstrained catching task.

Results

In Figure 13, representative curves of β in the nine conditions are displayed. The following qualitative observa-

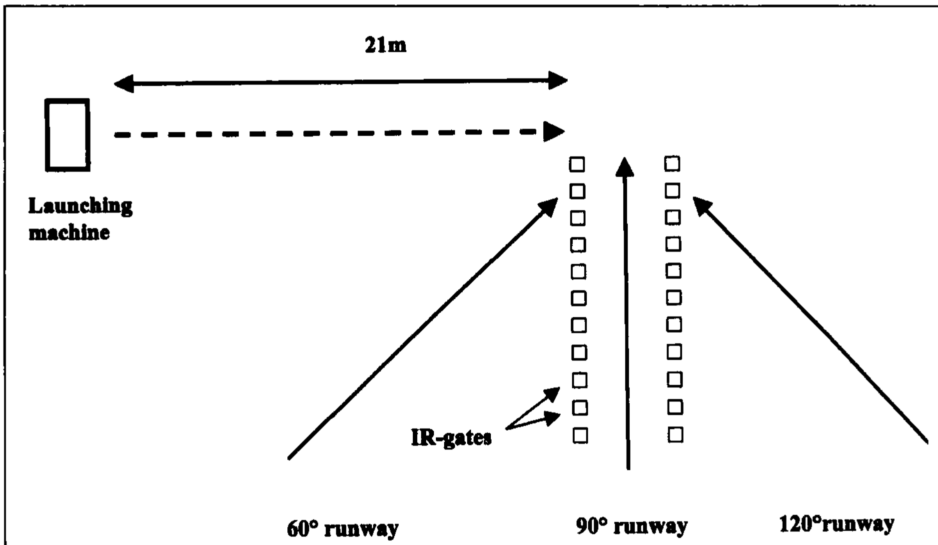

FIGURE 12. Top view of the experimental setup. The IR (infrared) gates for the 90° runway are shown. Between blocks of trials in one condition, the IR gates were moved to the next runway.

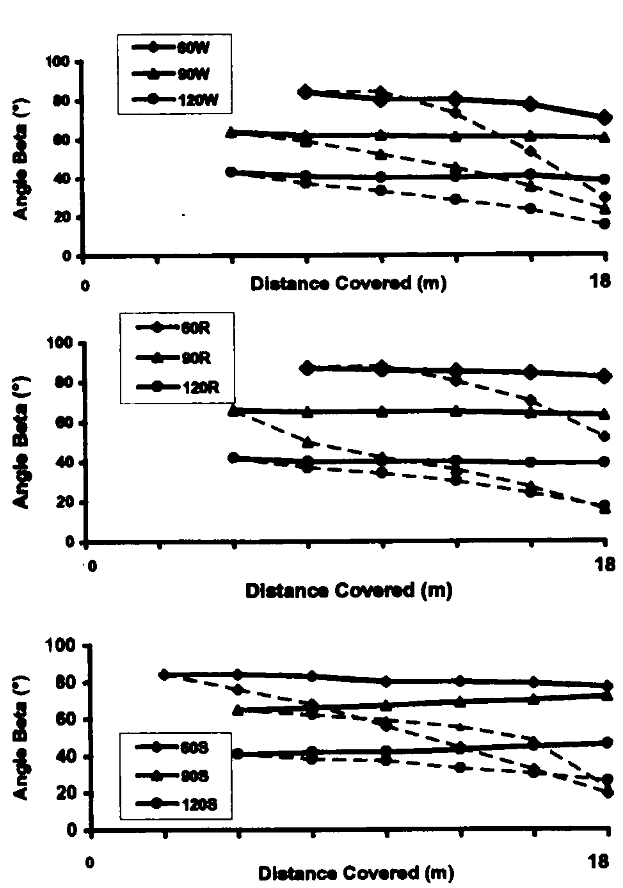

FIGURE 13. Evolution of angle Beta in the nine experimental conditions, a combination of walking (W; **top**), running (R; **middle**), and sprinting (S; **bottom**) and three approach angles (60°, 90°, and 120°), together with the simulations of a stationary observer (dashed lines). Typical plots of 1 participant are shown.

tions are worth noting here. In general, participants acted in such a way that changes in β were kept to a minimum. Only in Condition 60W was a decrease in β noticed. Furthermore, participants tried to keep β close to its initial value, even though that value ranged from 40° to 85°. Finally, the simulated curves quickly diverged from the real curves in all nine conditions, showing that the relevant EAS property β was available very early in the trajectory.

A 3 (initial angle) × 3 (initial velocity) repeated measures ANOVA on the slopes of the β curves revealed no differences for the approach angle variable, $F(2, 12) = 2.75$, $p > .05$, although there was a tendency in that direction (–0.750, –0.22, and –0.176 for the 60°, 90°, and 120° angles, respectively). No interactions were found. Slopes were more negative with decreasing initial velocity, $F(2, 12) = 9.882$, $p < .05$ (0.00, –0.24, and –0.92 for the sprinting, running, and walking conditions, respectively). Only the walking condition was significantly different from the other conditions. No interactions occurred. The $|r|$ values of the regressions were on average .772 ± .054. Repeated measures ANOVA showed no effects of speed or initial angle, and no interactions were found either.

The slopes of β over distance were significantly affected by the final outcome of each trial, $F(2, 18) = 24.027$, $p < .001$. Post hoc Newman–Keuls tests showed that late arrivals had slopes that were significantly smaller than those of the correct and early arrivals (+0.40, +0.04, and –0.82 for early, correct, and late arrivals, respectively).

The average slope of the regression of $d\beta/dt$ on the participant's acceleration was –1.272 ± 0.272, without significant speed or angle effects. No interactions occurred. The average $|r|$ value was .779 ± .121, ranging from .586 to .874 for the nine conditions. A significant effect of initial angle occurred, $F(2, 6) = 49.639$, $p < .001$, revealing that the lowest $|r|$ values occurred in the 60° condition (.651, .683, and .586 for walking, running, and sprinting, respectively).[1]

Discussion

The main result of this experiment was that the observed behavior was consistent with the findings from previous research (Lenoir, Musch, et al., 1999; Lenoir, Savelsbergh, et al., 1999) and with Experiments 1 and 2. Participants adapted their running velocity as a function of $d\beta/dt$, resulting in β curves that hardly changed during the approach. The relevant actor–environment property that was found to be necessary for an adequate (i.e., leading to a catch) velocity adaptation was available very early in the trajectory, as was shown by the simulations and the comparison between correct, early, and late trials.

In the 60° condition, participants had to catch up with the ball rather than go to meet the ball, whereas the inverse was true in the 120° condition. As a result, temporal constraints in the 60° condition were more stringent, and running at maximal speed was often necessary instead of a continuous adaptation as a function of $d\beta/dt$. That finding was expressed by lower $|r|$ values in that particular condition.

In the condition in which participants started walking, β tended to decrease. That tendency was a natural consequence of the fact that they were lagging behind more than in the other conditions. In spite of a continuous acceleration, they were not able to stop β from decreasing. As long as β was still larger than 0° at the time of their arrival at the interception point, however, a successful catch was possible.

GENERAL DISCUSSION

Our objective in this study was to provide evidence for the use of $d\beta e/dt$ as the EAS property that possibly modulates an observer's actions during the transport phase preceding the actual interception under varying circumstances. In Experiment 1, the velocity and the initial angular position of the ball were varied. We found that, even in those unpredictable initial circumstances, the observed behavior still fit with the nulling of the horizontal angular velocity of the ball. Furthermore, evidence was provided that changes in the velocity pattern are modulated by a spatiotemporal rather than by a purely positional property of the EAS, βe. In Experiment

2, the end-effector-centered strategy was tested over a range of head–end-effector distances. The results supported the view that successful behavior during the transport phase is characterized by nulling of the angular velocity of the ball with respect to the end-effector, whether contact is to be made with the head or with an external device 30, 60, or 120 cm away from the head. The better interception scores for shorter head–end-effector distances might show that βh still plays a part in final adjustments. In Experiment 3, it was demonstrated that the CBA hypothesis is a plausible explanation for the approach behavior during an unconstrained interception during locomotion.

So far, the proposed optical specification of the EAS property βe is not without debate. The current specification in Equation 1 is not completely satisfying in light of the interception scores in Experiment 2, indicating that accuracy increases as βe approaches βh, and thus that there might be a bias in the direction of the eyes. In addition, other elements of Equation 1, *l* and *d*, need to be integrated before βe is obtained, which might make the whole process more complex than is necessary. In this section, we describe how βe could be optically specified in an alternative way, that is, how the observer could perceive the (in)constancy of βe. Consider the geometry of an interception with an end-effector at a fixed distance from the eyes (Figure 14).

Observer and ball approach each other along the two legs of a V-shaped track. Variable *d* is the distance between the eyes and the end-effector; βe specifies the angular position of the ball with respect to that end-effector. In that particular task, an invariant βe can approximately be specified optically by the ratio of the angles βl and βr, a ratio that we will henceforth call lambda (λ). In Figure 15, the evolution of λ for invariant angles βe is shown. If βe is kept constant during the approach, λ is approximately constant until just before the interception. Consequently, the first derivative of λ could be a potential information source that observers rely on to keep *d*βe/*dt* close to constant and thus guarantee a timely arrival at the interception point.

Two characteristics dealing with the specification of λ need some further attention here. First, an invariant λ does not perfectly specify an invariant βe but should instead lead to a slightly increasing value of βe. For example, a perfectly constant λ will result in an increase in βe of about 3° for an initial βe value of 73°, a distance *d* of 60 cm, and an approach phase of 20 m from the interception point. Consequently, one might predict that if observers kept *d*λ/*dt* equal to zero in this particular task, βe would slightly increase, which should be reflected by a larger number of too early arrivals. The negative *CE* errors in Experiments 1 and 2

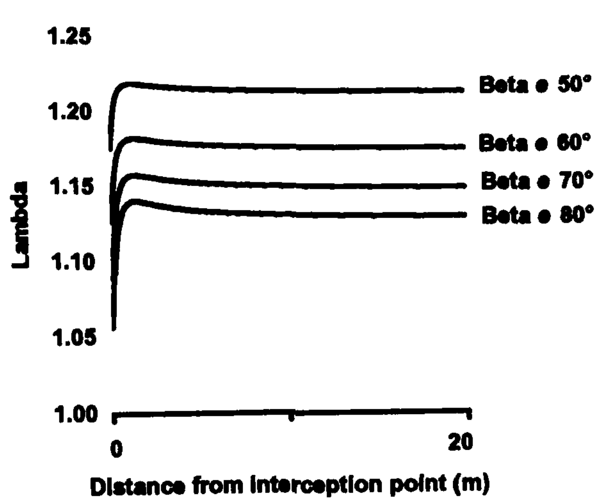

FIGURE 15. The evolution of λ, the ratio between βl and βr, for constant angles Beta e between 50°and 80°. See Figure 14 for definitions.

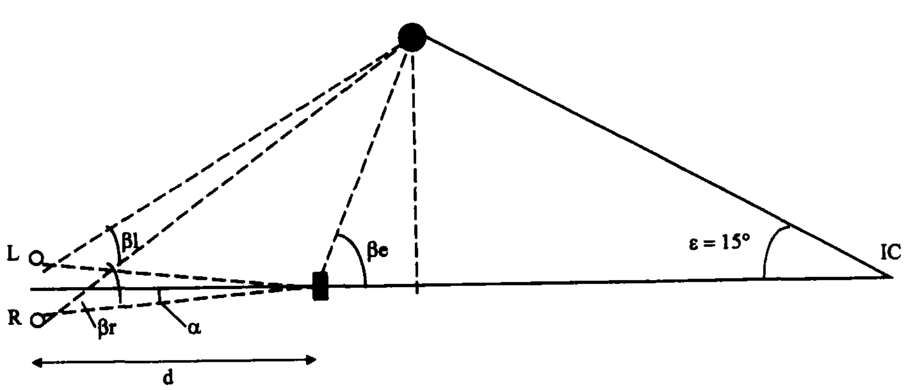

FIGURE 14. Geometry of the interception task. Observer and ball move along linear trajectories toward the interception point (IC). The end effector—the black rectangle—is at a fixed distance *d* from the eyes. Keeping Beta e constant will result in ball and observer arriving in IC at the same time. L, R, βl, βr, and ε = left eye, right eye, angle between the lines left eye–plate and left eye–ball, angle between the lines right eye–plate and right eye–ball, and angle between the two legs of the V-shaped track, respectively.

(Figures 4 and 10), which were a reflection of too early arrivals at the interception point, corroborated that prediction. An alternative explanation for the too early arrival is that participants might have deliberately used a safety margin: In sports situations, it is wise to arrive a little bit before the ball at the interception point.

Second, the sensitivity threshold for λ was apparently higher when the end-effector was farther from the eyes, as is shown in the simulation in Figure 16. When the observer remained stationary while the ball was moving, causing a rapid decrease in βe, λ increased sooner as the eyes–end-effector distance decreased. The findings of Experiment 2 were in line with that observation: Larger errors (*CE* and *AE*) were associated with increasing distances between the eyes and the end-effector. The participants also considered that the most difficult condition was intercepting the ball with an end-effector at 120-cm distance. Next to the specificity issue, one needs specific neural hardware for detection of angular ratios. Although it has been demonstrated that humans can detect angles (Regan, Gray, & Hamstra, 1996), one must be careful in extending that assumption to the detection of angular ratios.

The use of one single property of the EAS reduces the complexity of the control of an interception task during locomotion: No information on the exact location of the interception point or on the velocity of the ball is required. The observer does not need to know where he or she is going, only what to do to get there in time (see McLeod & Dienes, 1996). The use of that high-order variable is similar to the use of the optical expansion of an approaching object (tau) in long jumping, catching a ball, and jumping to hit a ball, or to the use of vertical optical acceleration in catching fly balls launched in the sagittal plane (Bootsma & Oudejans, 1993; Lee, Lishman, & Thomson, 1982; Lee, Young, Reddish, Lough, & Clayton, 1983; Michaels & Oudejans, 1992; Savelsbergh, Whiting, & Bootsma, 1991). In those situations, a coupling of one or a limited number of macroscopic optical variables to one or a few macroscopic movement variables is suggested, reducing a highly complex control problem to a coupling between a limited number of macroscopic parameters (Kelso & Kay, 1987). However, invariants such as tau, optical acceleration, and λ have their shortcomings. For example, tau correctly specifies the time remaining before contact only in head-on approaches and when the approach takes place at constant speed. Nevertheless, it has been demonstrated that tau is still used when those conditions are not met (e.g., Bootsma & Oudejans, 1993; Lee et al., 1983). Although *dλ/dt* does not exactly specify the relevant EAS property, our results indicate that it cannot be excluded (yet) as a potential optical variable that informs the actor on the (in)constancy of βe.

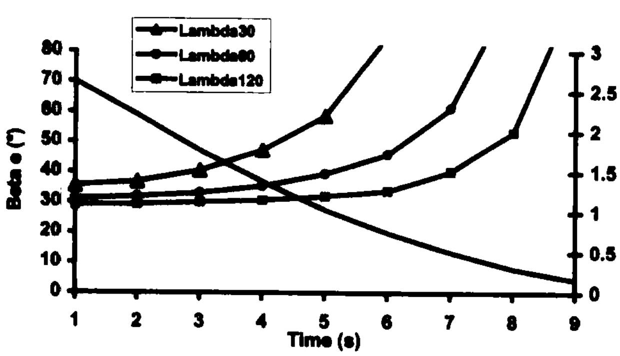

FIGURE 16. Simulation of the effect of a decreasing Beta e on λ for different eye–end-effector distances. A decrease in Beta e can be optically detected by an increase in λ; that increase is more pronounced as the distance between the eyes and the end-effector shrinks. See Figure 14 for definitions.

A strategy relying on the rate of change of an EAS property has nonnegligible advantages over a strategy based upon a static value. In the latter case, one needs several of the static values in order to know to what extent the actor–environment relation is changing and what actions are most appropriate in that situation. Such a strategy will lead to temporal delays, which is not the case with the *d*β*e*/*dt*-based strategy.

Our finding that the angular velocity of the ball with respect to the end-effector is a plausible candidate for the modulation of the observer's actions during the approach phase is a confirmation of previous results (Lenoir, Musch, et al., 1999; Lenoir, Savelsbergh, et al., 1999). But, as an illustration of an end-effector-centered strategy, our findings are not in agreement with the results of Michaels and Oudejans (1992) and Wann et al. (1993). Those investigators found, respectively, in a catching and a touching task that a head-centered strategy is abandoned near the end of the trajectory and that finer adjustments are performed on the basis of other information sources. In the present study (Experiments 1 and 2), the distance between the head and the end-effector was invariant, which could have made it more efficient for our participants to adapt the end-effector-centered strategy. Two implications of that more constrained task are (a) that final corrections by the exploitation of the degrees of freedom of the arm were excluded and (b) that any proprioceptive information about the position of the end-effector with respect to the head was excluded. It appears that taking the head or the end-effector as the center of reference is an issue that has to be considered within the constraints of the task in which it is tested.

Apart from the discussion on whether a strategy is head or end-effector centered, the CBA seems to be a useful strategy in dealing with the horizontal component of a ball's flight. The combination of canceling the vertical optical acceleration of the ball (Michaels & Oudejans, 1992) and nulling the horizontal angular velocity could guide a runner toward any fly ball, limited by the perceptual and running capacities of the observer. In spite of Tresilian's objections (Tresilian, 1995), both strategies seemed to be used simultaneously in a successful way: From all trials in Experiment 3, we post hoc reconstructed the curves of the vertical optical velocity (*dY/dt*). All curves linearly increased until shortly before the interception itself (with an average |*r*| value of .920 ± .041), a finding that replicates the results of Michaels and Oudejans (1992) and McLeod and Dienes (1993, 1996). That finding means that an invariant in the horizontal plane and an invariant in the vertical plane can guide the transport toward the interception point at the same time. In sum, the horizontal CBA strategy is useful in combination with the vertical OAC strategy as well as on its own, when only movement in the horizontal plane is involved.

NOTE

1. In this analysis, the acceleration value and the value of $d\beta/dt$ were obtained at the same moment, that is, when the runner crossed the IR gate. The lower registration frequency did not permit us to reconstruct and analyze the curves as thoroughly as in the first two experiments. That procedure resulted in our ignoring the visuomotor delay between the change in β and the participant's velocity adaptation. Although it is reasonable to assume that the delay is lower in running than in moving on a tricycle, the lower |*r*| values of the regressions might in part be the result of that procedure.

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APPENDIX

The starting point of the temporal measurement was when the ball reached the interception point (the projection of which was marked on the wall facing the camera). At that point, there were two possibilities:

1. The moment the ball was exactly at the interception point was visible on the frame. In that case, the distance *d* between the ball and the plate was measured to the nearest centimeter (for that purpose, a scale bar was indicated on the handlebar of the tricycle so that no parallax errors could occur). Overshoot and undershoot errors in milliseconds were calculated from distance *d* and the velocity of the ball. The velocity of the ball was constant during each trial and was recorded in each trial separately. Scores were rounded off to the nearest 50 ms.

2. The arrival of the interception point fell between two consecutive video frames. In that case, the distance between the plate and the ball was measured on the frame before and after the arrival of

the ball. Between both frames, the ball traveled a maximum distance of between 6.2 cm (at the lowest velocity of 1.55 m/s) and 10.5 cm (at 2.63 m/s). The distance between the ball and the plate did not measurably change, making linear interpolation justified. Then the same procedure as in 1 was followed.

All interception scores in Experiments 1 and 2 were obtained by means of a 25-Hz video, equivalent to 40-ms accuracy. The resulting—significant—differences between conditions were often much smaller than that value, which required additional evidence that those differences were reliable. Therefore a tennis ball was attached to a 2-m-long pendulum, which was swung over gap distances between 3 and 12 cm at velocities between 1.2 and 3.0 m/s, similar to the gap distances and velocities in Experiments 1 and 2. Gap passages of 64 trials were simultaneously filmed at 200 Hz (reference value) and 25 Hz. From the 25-Hz images, we obtained passage times by means of interpolation, as we had done in Experiments 1 and 2. The veridical time values (200 Hz) were plotted against the 25-Hz values, and a linear regression was performed. The regression equation was $Y = 1.015x - 0.2415$, with $r^2 = .9906$ for all 64 passage times. The r^2 was higher (.9632) for the longest gaps (between 40 and 80 ms) than for the shortest gaps (between 10 and 25 ms, $r^2 = .87$). Data and linear regression are shown in Figure A1.

Submitted November 17, 1999
Revised March 6, 2001

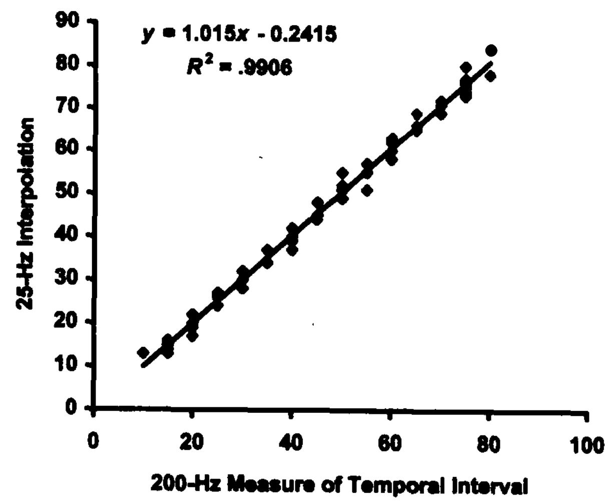

FIGURE A1. Linear regression of passage times, filmed at 25 and 200 Hz.